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14. ABSTRACT
The overall objective of this project was to use tools from nonlinear chaos theory to gain a better fundamental understanding of vibrating cable flows. To accomplish this objective, low-order models based on iterative maps were developed. These models (or coupled map lattices) are highly efficient, and should have future application for flow control of vibrating cables. Specific capabilities developed during the course of the project include; 1) incorporation of self-learning features (neural networks) that allow the models to learn directly from a cable flow, 2) addition of control strategies into the models, and 3) integration of a structural dynamics model with the coupled map lattice. Numerical simulations and experiments on vibrating cables were also conducted to validate the models. At their current state of development, the models can predict certain observed features of cable flows, including cable vibration amplitudes and flow patterns. In addition, we studied an experimental technique that uses ultrasonic acoustic pulses to measure lift forces on vibrating structures.

15. SUBJECT TERMS
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Report WPIAE-DJO-03-1

Low-Dimensional Modeling of Flow-Induced Vibration with Coupled Map Lattices

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GOALS

The goal of this project is to use tools from the study of nonlinear dynamical systems to gain a better fundamental understanding of fluid-structure interaction problems in vibrating cables. In addition, adaptive control theory is incorporated into low-dimensional iterative models that predict certain aspects of vibrating cable flows. We have also sought to develop an experimental technique that can aid in understanding of circulation generation and lift forces in vibrating cable flows.

OBJECTIVES

We seek to continue to logically extend the development of a coupled map lattice (CML) model in order to predict vibrating cable flows using low-dimensional models. This flow has recently received increased attention since many offshore structures, such as towed bodies, incorporate flexible cables exposed to hydrodynamic flows. The expected outcomes of the study will be; 1) advances in the state-of-the-art in combined fluid-structural modeling through comparison of the CML models with the NEKTAR spectral element simulations of G. Karniadakis, in addition to experimental data from laboratory wake flows, 2) extension of the coupled map lattice model to include modeling of wake-cable coupling and fluid loadings for freely vibrating cables; and 3) development of *self-learning, adaptive coupled map lattice models* in which the coupled map lattice model learns from NEKTAR simulations and laboratory wake flows. Eventually, these models could be used in real-time control algorithms to manipulate vortex shedding patterns at low Reynolds number.

APPROACH

A combined analytical-experimental approach is used with some numerical aspects also being incorporated. Analytical aspects focus on the continued development of low-order models that utilize a series of diffusively coupled circle map oscillators along the cable span. Experimental work focuses on continued experiments on vibrating cables in the WPI water and wind tunnels using hot-film rake measurements to obtain wake patterns behind flexible cables and bluff bodies. Numerical work focuses on use of the NEKTAR spectral element code of G. Karniadakis at Brown University in independent runs conducted on the WPI IBM supercomputer. We have also further developed an ultrasonic circulation technique that can yield circulation (lift) values in the unsteady and spatially

varying flows that characterize vibrating cable wakes. The work this year was conducted by the principal investigators and by two Ph.D. candidates (G. Balasubramanian and J. Yuan).

WORK COMPLETED

The primary work completed during the course of the entire project includes;

- Development of a highly efficient coupled map lattice (CML) model for wake patterns behind vibrating cables. The CML incorporates a series of diffusively coupled circle map oscillators along the cable span. This CML was shown to predict wake patterns (lace-like, oblique, traveling waves) observed in wake simulations and experiments.

- Incorporation of control strategies into these CML models. Proportional, adaptive proportional, and discontinuous nonlinear control methods were applied. These CML models and control strategies may be suitable for implementation in wake experiments with further development.

- Incorporation of additional physical effects (convection processes and spanwise velocity distributions) to our CML model yielding a convective-diffusive CML. The convective-diffusive CML provides the framework for the self-learning CML discussed next.

- Addition of an adaptive estimation scheme to the CML models resulting in an adaptive, self-learning model that can precisely mimic vortex shedding patterns simulated in the NEKTAR code.

- Addition of a new neural network based estimation scheme to the CML models resulting in an adaptive, self-learning model that can better mimic vortex shedding patterns simulated in the NEKTAR code or measured from experiments.

- Development of a new coupled map lattice that incorporates a structural dynamics model to study freely vibrating (as opposed to externally forced) cables. This allows predictions of cable response amplitudes in addition to wake dynamics and structures.

- Development of an ultrasonic circulation measurement technique applicable to fluid-structure interaction experiments and unsteady flows.

The primary work completed during the past year has been;

- Continued development of neural network based estimation scheme in the CML models resulting in an adaptive, self-learning model that can better, and more efficiently, mimic vortex shedding patterns simulated in the NEKTAR code or measured from experiments. The self-learning CML is now applied to vibrating cables with a sheared freestream flow.

- Experiments on flexible cable and cylinder wakes yielding experimental wake patterns that are then estimated with previously developed self-learning CML models, including the neural network based scheme.

- Continued development of an ultrasonic circulation measurement technique that we show to be applicable to measuring (circulation) lift forces in bluff body flows.

RESULTS

This results section reflects work completed during fiscal year 2002 only. We have continued to develop and extend our neural networks based, self-learning CML. We can now accurately *estimate shear layer flows* modeled in NEKTAR simulations (through a spanwise variation in freestream velocity) as shown in Fig. 1(a). The wake pattern from NEKTAR exhibits a combined lace-like-oblique structure which is efficiently estimated within several shedding cycles. We have also made certain improvements in the neural networks CML that lead to *enhanced efficiency* compared to our previous self-learning CML's (multi-variable least squares approach, Balasubramanian et al. 2002) as shown in Figure 1(b).

In the past year we have studied whether the self-learning CML models can accurately estimate *experimental wake patterns* from laboratory experiments. We have utilized hot-wire rake studies and correlation techniques (described in Balasubramanian et al. 2002) to measure appropriate wake patterns behind flexible cables and rigid cylinders in both the WPI water and wind tunnels. Figure 2 shows a typical lace-like pattern measured behind the flexible cables in these experiments, compared to NEKTAR predictions. The self-learning CML is shown to effectively estimate the experimental wake patterns in an off-line mode.

In addition, we have continued our development of an ultrasonic circulation measurement (UCM) technique useful for fluid-structure interaction studies. This low-cost measurement technique is based on propagation of sound waves around a path enclosing an oscillating bluff bluff body, for example. The technique has been described in greater detail in a previous annual report (Olinger, 1997). Our work has largely focused on extending the UCM technique to unsteady and spatially varying flows, characteristics inherent to flexible cable flows. We have shown (Yuan & Olinger, 2002) that a relationship between measured circulation Γ and resultant lift force for unsteady flows of the form

$$C_l^{(3)} = \frac{2\Gamma(t)}{Ud} + \frac{2R(d\Gamma/dt)}{U^2} \qquad (1)$$

where R = ¾ for oscillating flat plate flows, R = 1 for impulsively started flat plates, R is a complex function for pitching flat plate flows, and most importantly R = 0.4 for low Reynolds number cylinder wake flows. The first term in eq.(1) is the standard Kutta-Joukowski assumption, while the second term models unsteady effects. The variable R can be shown to constitute a non-dimensional streamwise dimension (R = x/D = 0.4). This shows that the near wake region where primary vortex formation occurs seems to dominate the wake-structure coupling leading to lift generation.

We have also extended these ideas to focus on the open question of how flowfield data (vorticity, circulation etc.) can be interpreted to predict unsteady lift forces on bluff bodies (Unal et al. 1997; Noca et al. 1997). We have confirmed through numerical simulations that global UCM circulation measurements can be used to accurately predict lift forces on bluff bodies (see Fig. 3). The addition of a wake vortex effect, (Lighthill, 1986; Yuan, 2002) through

$$C_l^{(3)} = \frac{2\Gamma(t)}{Ud} + \frac{2R(d\Gamma/dt)}{U^2} + C_{l\ wake\,vortex} \quad (2)$$

improves the accuracy of the prediction. This wake vortex term requires measurement of circulation (vortex strength) distributions in the streamwise direction in the wake using UCM.

IMPACT/APPLICATIONS

The coupled map lattices provide very efficient low-order models for flow-structure interaction in cylinder wakes with computational times on the order of 10-100 shedding cycles per CPU second. Beyond their use as flow models in adaptive wake control schemes as described earlier, the adaptive estimation schemes could be coupled with other flow models/simulations (Navier-Stokes solvers, etc.) resulting in potential for use in a wide range of applications. The ultrasonic measurement technique can help investigators in fluid-structure interaction applications gain a better fundamental understanding of unsteady and spatial effects in these flows.

TRANSITIONS

None

RELATED PROJECTS

We have continued our interactions with G. Karniadakis (Brown University) through independent runs of his NEKTAR code on the WPI IBM supercomputer.

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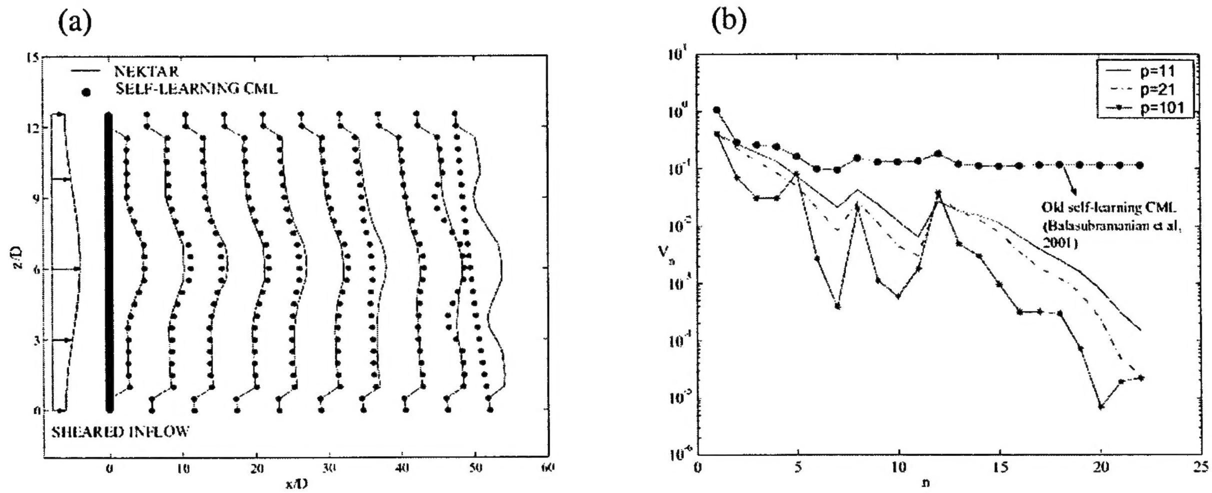

Figure 1. (a) Neural-networks based CML applied to flexible cable wake with sheared freestream flow.(b) Efficiency of neural-networks based CML compared to earlier self-learning CML. The state error V_n is a measure of the difference between the two wake patterns in (a). The parameter p refers to the number of neural networks applied.

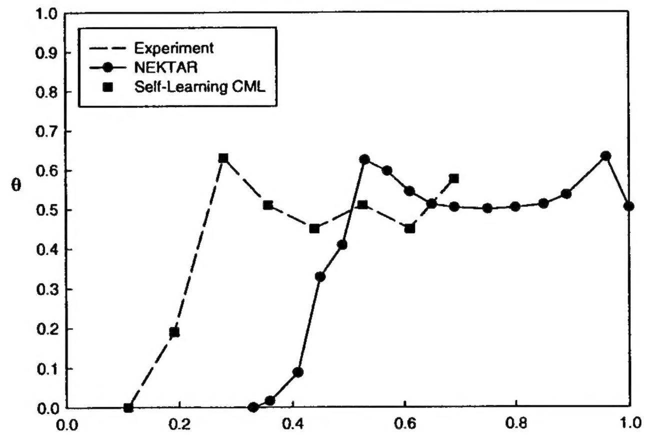

Figure 2. Comparison of wake patterns from the neural-networks based CML, laboratory wake experiments for a freely vibrating flexible cable in the WPI water tunnel, and NEKTAR simulations. The addition of neural networks to the low-order wake models allows for efficient estimation of wake patterns from laboratory experiments. The spanwise shift in the experimental wake pattern is believed to be due to different boundary conditions in the experiments compared to the NEKTAR simulation.

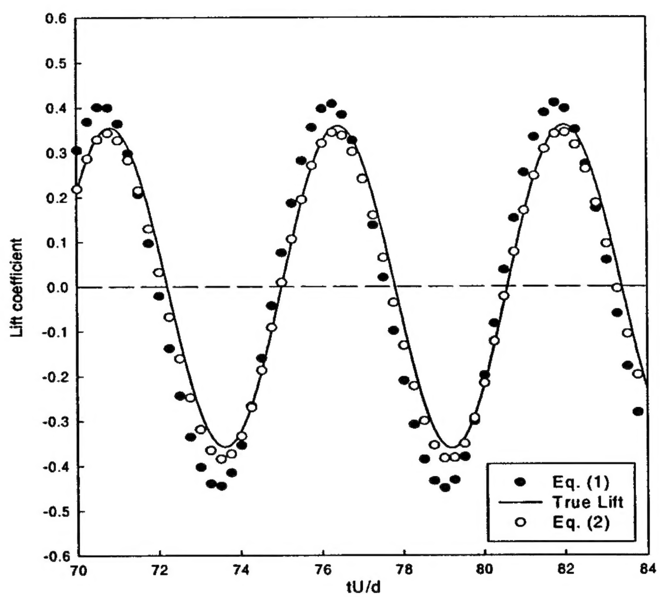

Figure 3. Lift coefficient vs. time from numerical simulations of a rigid circular cylinder at Re = 100. The symbols represent lift models, eq. (1) and (2), that convert flowfield data (circulation) into unsteady lift forces on bluff bodies, developed in work on the ultrasonic circulation measurement (UCM) technique.

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